A Review of Fish Response to Spillways

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FOREWORD

This review represents a portion of a study undertaken by Montreal Engineering Company, Limited, on behalf of the Canadian Electrical Association, to examine fish mortality as a function of spillway characteristics. The objectives of the study were to assess potential problems associated with fish passage over spillways in Canada and to prepare preliminary guidelines for spillway design and operation so as to eliminate or mitigate their impact on fish. The study involved a review of both published and unpublished literature, visits to current projects where fish response to spillways was under investigation, and an assessment of fish-conservation problems associated with spillways in Canada.

ABSTRACT

Ruggles, C.P. and D.G. Murray. 1983. A review of fish response to spillways. Can. Tech. Rep. Fish. Aquat. Sci. No. 1172. ix + 31 p.

Juveniles from most fish taxa will pass downstream, over or through spillways, if outlet flow is sufficient. Fish passing over relatively high spillways may be injured by rapid pressure changes, rapid deceleration, shearing forces, turbulence, abraison and the striking force on the water in free fall. Injuries begin to occur when impact velocity of a fish striking a water surface exceeds 16 metres per second. Water below some spillways may become supersaturated with atmospheric gas to an extent that gas-bubble disease in fish may occur. Flow deflectors placed near the base of spillways have been successful in reducing the deep plunging action which is responsible for air entrainment and subsequent nitrogen supersaturation. Spillways are not currently perceived to be a serious source of fish mortality in Canada, although nitrogen supersaturation below spillways was identified as a potential fish-conservation problem in three rivers in British Columbia. Guidelines are presented which provide design and operating suggestions for spillways to eliminate or reduce their impact on fish.

Key words: Downstream fish passage through dams, spillways, hydraulic characteristics, dams, migration, mortality, gas-bubble disease, gas supersaturation of water.

RÉSUMÉ

Ruggles, C.P. and D.G. Murray. 1983. A eview of fish response to spillways. Can. Tech. Rep. Fish. Aquat. Sci. No. 1172. ix + 31 p.

Les jeunes de la plupart des taxons de poissons franchiront, dans le sens du courant, un déversoir si le débit est suffisant. Les poissons passant par-dessus des déversoirs relativement élevés peuvent subir des blessures par brusques changements de pression, décélération rapide, forces de cisaillement, turbulence, abraison et impact de l'eau en chute libre. Il y a danger de blessures à partir du moment où la vitesse d'impact d'un poisson à la surface de l'eau dépasse 16 m par seconde. Il se peut aussi que l'eau en aval des déversoirs soit sursaturée de gaz atmosphériques et que les poissons soient atteints de la maladie des bulles de gaz. Pour empêcher l'emprisonnement de l'air et la supersaturation d'azote qui s'ensuit, on a placé des déflecteurs près de la base des déversoirs. Pour le moment, ces structures ne sont pas considérées comme cause importante de mortalité des poissons au Canada, bien que, dans trois rivières de la Columbie-Britannique, on ait constaté que la supersaturation en azote en aval des déversoirs pouvait poser des problèmes de conservation des poissons. Des lignes directrices sont données concernant le dessein et le fonctionnement des déversoirs afin d'éliminer ou de minimiser leur impact sur les poissons.

INTRODUCTION

This review addresses the impact on fish of spillways at dams. Factors such as fish behaviour and entrainment at spillways, fish mortality directly related to spillway design and operation, and methods to minimize or eliminate fish mortality resulting from spillways are considered. The review does not address the problem of how spillways affect the upstream migratory behaviour of adult anadromous fish or how dams effect wide-scale changes to the terrestrial and aquatic environments. The latter questions are addressed in excellent reviews by Larkin (1972), Baxter (1977), and Baxter and Claude (1980).

Most of the research that has been conducted on fish response to spillways has not been reported in the scientific literature. Much of the information is contained in manuscript reports and agency progress reports. Some of the experimental results appear to contradict others; thus, many of the conclusions reached must be considered tentative. Despite these shortcomings, a critical review of both published and unpublished information concerning fish mortalities related to spillways represents a necessary step in the utilization of presently available knowledge to eliminate or mitigate these detrimental effects. Such a review serves to point out deficiencies in existing knowledge and identifies productive areas for future research.

In the following sections, fish behaviour at spillways, factors affecting mortality and methods developed to minimize mortality are critically reviewed. Following this review of literature, a brief description of some common types of spillways is presented, along with observations on how their hydraulic characteristics affect fish mortality. An overview of fish-conservation problems associated with Canadian spillways is presented, followed by guidelines for spillway design and operation to minimize mortality.

In a recent paper (Ruggles 1980) considerable material dealing with Atlantic salmon mortality at spillways was reviewed. We have borrowed extensively from this earlier work, and the relative information is repeated here for the sake of providing a more complete account of how a variety of fish respond to spillways. Where appropriate, the material was updated to reflect new information that has come to light since the earlier review on downstream Atlantic salmon migrations.

BEHAVIOUR AND ENTRAINMENT

Several studies (Hamilton and Andrew 1954; Schoeneman and Junge 1954; Vernon and Hourston 1957; Mills 1964; Munro 1965; Farwell 1972; Raymond and Sims 1980; Ruggles 1980) on downstream migrating salmonids present observations that indicate certain species of Pacific salmon (genus Oncorhynchus), steelhead (Salmo gairdneri), and Atlantic salmon (Salmo salar) are reluctant to sound to submerged outlets at dams, especially if the outlets are located at a depth greater than about 20 metres. Juvenile salmonid migrants are most apt to use surface outlets if discharges through them are sufficient.

At the 76-m-high dam on the Baker River in Washington State, schools of juvenile sockeye (Oncorhynchus nerka) and coho (O. kisutch) migrants swam with the current as they approached the spillway opening. As the fish drew closer to the spillway and velocities increased, they turned and commenced to swim against the current while being drawn towards the gate opening. On entering the gate, the fish swam vigorously, but were swept over the spillway by the high velocities at this point (Hamilton and Andrew 1954).

Ruggles and Ryan (1964) observed wild coho and sockeye salmon smolts migrating at dusk in an experimental flume in Robertson Creek, British Columbia. Schools of sockeye smolts were observed to orientate to the direction of the flow differently, according to the velocity of the flow. At slow velocities of about 0.4 m/s, most of the fish entered the flume swimming downstream headfirst. At intermediate velocities of about 0.8 m/s, sockeye smolts appear to be transported passively downstream. Although the individuals of a school maintained their position relative to one another, the direction in which they were orientated with respect to the current appeared to be random. At velocities of about 1.2 m/s, juveniles were carried downstream tailfirst and entered the flume orientated head upstream. The 45-m-long flume intercepted naturally migrating fish which entered volitionally. Water velocities were controlled by means of atoplogs at the downstream end of the flume.

Above the Cleveland Dam, on the Capilano River in British Columbia, schools of 50-100 coho and steelhead smolts were regularly observed near the surface of the forebay during periods when spilling was not taking place (Vernon and Hourston 1957). These authors pointed out that the normal migratory behaviour changed from that conducive to rapid seaward migration toward schooling and feeding - behaviour best suited to survival at sea.

Seaward-migrant salmon, however, are capable of sounding to considerable depths to find egress from a reservoir when a surface exit is not available to them. Under such conditions, they will usually delay in the forebay, sometimes for weeks, causing abnormal concentrations immediately upstream of the dam. During this period, the reservoir may become thermally stratified and further inhibit fish from sounding and passing through the zone of temperature change in order to use the submerged exit. Both coho and sockeye smolts sounded to a depth of 29 m to

migrate through the turbine intake when surface spill was not available at Baker Dam (Hamilton and Andrew 1954).

At Baker Dam, one of the most important factors apparently influencing the choice of exit from the reservoir was the approach velocity in the vicinity of the spillway and turbine entrances. Two almost distinct flow patterns were set up in the forebay when the reservoir was full and spilling was in progress. Water discharged over the spillway was drawn largely from the surface layers. The tunnel intake, located between the 25-m and 32-m levels, drew little or no water from the upper six metres at full reservoir. Surface-migrating salmon at times during surface spill were drawn to the spillway exits because the prevailing flow was in that direction. When there was no spill, the only remaining attraction was in the direction of the tunnel, but this was not evidently sufficient to induce significant numbers of fish to take this route. Over 90% of the seaward migrants used the spillway exits during the 2-year study period.

Schoeneman and Junge (1954) showed that chinook salmon smolts sounded to a depth of 20 m to egress from a reservoir on the Elwha River in Washington State when other exits were not available, but chose a surface exit when such a route was available. Coho smolts, on the other hand, rarely sounded to obtain egress from the forebay but remained in the reservoir until surface spilling occurred.

Juvenile salmonids have often been observed passing over spillways during daylight hours, apparently refusing to sound to turbine intakes, even though most of the flow was through the turbines. If no spilling is occurring during the day, the migrants will not use the turbine route until after dusk. Recent sonar observations at John Day Dam demonstrated that steelhead and chinook salmon migrating at dusk showed no preference between spills occurring from approximately 12 m below surface and from the surface. Testing is continuing to better define the most effective spill patterns to attract downstream migrants over the spillways. Stoplogs are placed upstream of the gate to create surface spills through the gates.

Raymond and Sims (1980) tested diel movement patterns of chinook salmon smolts associated with surface spills and with turbine passage. Sampling in turbine-intake gatewells and at spillways showed that most smolts that migrated by way of the turbines entered the intakes after dark, normally between dusk and 0100 hours. Smolts moving through the spillway showed predominant daytime movement, with peaks occurring in the morning and late afternoon. They concluded that surface spilling at John Day Dam had significant downstream salmon-passage potential, including reduction of migrational delay in the forebay.

Tests conducted at a small dam (3.1 m in height) on the Holston River in Tennessee showed that all larval fish taxa in the water column immediately upstream from the dam, and hence available for passage, did indeed pass over the dam. Eggs, larvae and juveniles of 24 taxa were collected during the study. Dorosoma sp. (unspecified shad), Catostomidae (unspecified suckers), and Morone chrysops (white bass) were the major taxa (Graser et al. 1979).

A variety of authors have described fish losses over spillways located on relatively small dams. The "losses" are actually fish escaping from the reservoirs and were considered important only as they affected fish harvest from the reservoirs. Losses usually occur in the spring and are species specific. Lewis et al. (1968), reporting on fish movement over a small spillway located on the outlet of an artificial 70-acre impoundment in Illinois, reported bullhead (Ictalurus melas) escapement occurred at night and bass (Micropterus salmoides) escapement during the day. Clark (1942) reported that on a small headwater lake in Ohio fish movement over a spillway took place during the spring spawning season. The species were the bluegill (Lepomis macrochirus) and the white crappie (Pomoxis annularis). Not all species in the study lake were captured below the spillway, indicating that only certain species were prone to leave the lake. Powell and Spencer (1979) reported on fish losses over a small spillway located on a dam on the outlet of a 37.6-ha public-fishing lake in central Alabama. At least 400 white catfish (Ictalurus catus) left the lake over the spillway during April and May, but losses did not occur later in the year.

In addition to fish going through and over spillways, a number of instances have been reported where fish have tended to concentrate below spillway structures. At the Lobstick control structure, associated with the Churchill Falls power development in Labrador, large numbers of whitefish (species not given) congregate in the immediate vicinity below the control gates during the period June-October. The reason for this mass congregation is not known. Periodically, the gates are closed for inspection or emergency repair, and fish congregate in the gate bays and in pools outside the wingwalls. When the gates start to reopen, surface return currents in the stilling basin transport fish into the gate bays and hurl them against the gates, wing and splitter walls. These conditions occur only when the gates are open between 0 m and 1.8 m. Once the gates exceed this elevation, hydraulic conditions change and fish are swept out of the gate bays. Up to 10,000 fish have been reported killed. With the technical help of the Department of Fisheries and Oceans of Canada, the Newfoundland and Labrador Hydro are committed to develop a solution to the problem (Montreal Engineering 1979, Appendix II).

The season during which spilling occurs will have an effect on potential fish mortality problems at spillways. In the case of storage dams, if spilling does not occur when downstream migrating fish are present, a physical barrier is created that prevents normal fish movement. Such an impediment to anadromous and catadromous species could prevent them from completing their normal life cycle.

There is often a reluctance on the part of downstream migrants to migrate through stratified reservoirs. Delays while migrating through a reservoir, plus warming of the surface waters, may create a "temperature blanket" that can trap smolts in the reservoir (Foerster 1937). In some cases, the smolts resume their seaward migration in the next spring (Munro 1965; Raleigh and Ebel 1967); but in others, they may spend their entire life cycle in fresh water (Collins et al. 1975). Many migrants appear to lose their urge to migrate when their biological clocks run out of time allotted to make the transition from fresh to salt water. The sockeye salmon population of the Snake River, Idaho, has completely adjusted to a freshwater life cycle, and remnants of the anadromous runs now remain as the landlocked variety known as kokanee (Raleigh and Ebel 1967).

In a five-year study of the effects of a large impoundment on the migration of anadromous fish, Raleigh and Ebel (1967) presented data on the physical and chemical factors responsible for determining the distribution and timing of juvenile chinook, coho and sockeye salmon attempting to migrate downstream through the 6,000-ha Brownlee Reservoir on the Snake River, Idaho. These studies revealed that escapement of juveniles from the reservoir was least successful when the reservoir was full and when currents were random and slow. Escapement was intermediate when drawdown was moderate and downstream flow more pronounced. The best escapement (almost 100%) occurred when drawdown was large and the reservoir current was well oriented downstream. Mortality was high among juvenile salmonids that did not complete their migration through the reservoir in the spring of the year of entry. Juveniles still in the reservoir in August and September were restricted to marginal habitats between zones of high temperature in the epilimnion and low oxygen in the hypolimnion.

MORTALITY FACTORS

In the early stages of hydroelectric development, fishery workers were preoccupied with providing upstream fish-passage facilities at dams to ensure continued access to freshwater spawning and rearing grounds for anadromous and catadromous fishes. Passage over spillways was not considered to be a particularly important cause of mortality to downstream migrating fish.

It was evident from the beginning that juvenile anadromous fishes were able to withstand considerale turbulence and pressure changes, since commercially important runs of salmonid fishes existed under natural conditions where the young were required to descend over falls with head differences of six metres or more. Furthermore, experiments at an impassable barrier for upstream migrants, a chute-type falls 27 metres high on the Skykomish River in Washington State, indicated juvenile coho and chinook salmon and steelhead trout were able to successfully descend. Adults of all three species are annually trapped at the falls and hauled above to make use of suitable spawning and rearing habitat (Bell and DeLacy 1972).

A number of factors may, however, directly or indirectly cause mortality of fish at spillways. Available information on these factors is reviewed in the following sections.

DIRECT PHYSICAL INJURY

In addition to incurring internal injuries, fishes that pass over spillways often suffer injuries to the skin. Hoar (1956) pointed out that the skin of fishes forms a barier between the external environment and the internal fluid environment of the living cells. Injury to the skin results in:

1. Flooding of tissues with excessive amounts of osmotic water.
2. Liberation of toxic materials from injured tissues.
3. Penetration of pathogenic organisms.

When fish are in freshwater, there is a continuous flow of water into the body through the gills and mouth. The kidney must function continuously to excrete relatively large volumes of water. If additional volumes of water enter through injured skin, an abnormal accumulation of fluids within the tissues may lead to death.

Studies of vertebrate animals have shown that injured tissues frequently liberate histamine-like materials which are toxic and which markedly increase tissue permeability. An increase in tissue permeability would accentuate inflow of water and loss of vital tissue constituents such as salt and plasma protein.

Often, fungus infection occurs at the site of skin abrasions. The fungus attaches to the fish by means of small, root-like filaments that penetrate the skin. In late stages of infection, the filaments may invade the underlying musculature; and as the filaments grow, they cause the death of surrounding tissues and may eventually lead to the death of the fish.

Considerable research in the western

United States and in British Columbia with Oncorhynchus sp. and steelhead trout provides a basis for estimating the degree and nature of mortality that fish might be subjected to when passing over spillways at dams. Bell and DeLacy (1972) review a wide variety of experiments and observations concerning the success of juvenile fish passage from heights (Table 1).

Data presented by Silliman (1950) and Cleaver (1967) on adult salmon and steelhead returns suggest that juvenile salmonids did not experience significant mortalities at the Bonneville Dam (total head 26 m) on the Lower Columbia River. Most seaward migrants used the spillway route in these early years, since there was little water used for power generation compared to the total flow of the river. In experiments at McNary Dam (total head 27 m), on the Columbia River, Schoeneman et al. (1961) estimated mortality of chinook salmon yearlings passing over the spillway to be 2%, with a 95% confidence interval from 0% to 4%.

At Glines Dam on the Elwha River in Washington State, yearling coho salmon suffered an average mortality of 8% when passing over the 60.6-m-high spillway. The spillway was the free-fall type, discharging by way of an extended apron and dropping the flow 55 metres directly into a pool. The quantity of spill, regulated with 0, 0.5 and 2.4 metres of gate opening, did not affect the rate of mortality (Schoeneman and Junge 1954). On the same river at the Lower Elwha Dam, with a contained-flow type spillway and a head of 30.3 metres, yearling coho suffered an average of 37% mortality. These results appear to demonstrate the effects on fish mortality of two different spilling conditions.

Fish at the Glines Dam fell directly into the stilling pool, either falling free from the column of water in which they started the spill, or falling contained within that column of water. The spillway at the Lower Elwha Dam, however, is built on rock outcropping and has a number of obstructions in its floor; thus, the water cascades in a highly turbulent manner before entering the stilling pool. Fish would be subjected to tumbling and shearing forces within the water and possibly to striking the bottom or side walls of the structure. It appears that the manner in which energy is dissipated in the spillway can have a profound effect on fish mortality rates. Spillways which dissipate energy at a slower rate may improve the chances for fish survival.

Recent data presented by Raymond and Sims (1980) show that mortality of juvenile chinook salmon passing over the spill and through the spillway tailwater at John Day Dam (total head 32 m) on the Columbia River was not significantly different from 0 at the 95% confidence level. Results based on releases of marked test and control fish showed computed survivals of two experiments to be 96.5% and 119%, respectively. An average of 2% is accepted as the best estimate of spillway-related mortality at Columbia and Snake River dams (Washington State Department of Ecology 1980).

After the construction of the high-head Baker River Dam (total head 76 m) in Washington State, it became evident that juvenile salmonid migrants were being harmed in their descent (Hamilton and Andrew 1954). Similar findings at the Cleveland Dam on the Capilano River (total head 73 m) in British Columbia were reported by Vernon and Hourston (1957).

During spillway passage at high dams, fish may be endangered by any of the following conditions:

1. Rapid pressure change.
2. Rapid deceleration.
3. Shearing effects.
4. Turbulence.
5. Striking force of fish on the water in free fall.
6. Scraping and abrasion.

Unfortunately, detailed experiments have not been conducted that can elucidate the relative importance of these factors in causing fish mortality. Factors that have been identified include impact against the base of the spillway, abrasion against the rough concrete face of the spillway, and various forces associated with deceleration after fish reach the surface of the tailwater pool. Injuries sustained included abrasions, eye damage, embolism and hemorrhaging.

Concern for the passage of fish over high dams led to experiments on fish under free-fall conditions. Smith (1938) and Holmes (1939) proved that 5-cm to 10-cm salmon could survive free falls of up to 56 metres. Studies at Glines Dam on the Elwha River, Washington, where spill over the crest of the dam falls free for 55 metres into a pool, showed a survival of 92% for yearling coho salmon (Regenthal 1957). In these early experiments, no measurement was made of the rates of descent or terminal velocities reached by the free-falling fish.

As work progressed on free-fall survival of juvenile salmonids, it became evident that knowledge of the rate of fall was required to interpret the results of research conducted under a variety of experimental conditions. At the University of Washington, studies in which fish were air dropped, and in which simulated fish shapes were observed in a wind tunnel, established terminal velocities of approximately 16 m/sec for fish in the size range of 10 cm-13 cm. Fish in the 60-cm range had terminal velocities in excess of 58 m/sec. The smaller fish reached their terminal velocity in falls of approximately 30.5 metres. The larger fish continued to accelerate in drops of up to 213 metres. Actual tests with live sockeye salmon (Oncorhynchus nerka), showed that fish about 18 cm long reached a terminal

TABLE 1. Survival of downstream migrants at spillways (from Bell and DeLacy 1972).

Place	Type spill	Total head (ft)	Est. max. vel. (fps)	Discharge (cfs)	Species	Size	Number of fish		Percent survival		Remarks
							Control	Test	Control	Test	
McNary & Big Cliff	Ogee & buck. Bucket	85-90	±83	1,800	Fall chinook	2 - 6 in.				98	
Bonneville	Ogee & buck.		±64		Chinook	Fingerling	Many tests			54.2 to 98.5	Balloon tests
McNary	Ogee & buck.	85	±83								
Elwha	Chute		>40								
Elwha	Chute	100	>40		Chinook	Fingerling	15,646	16,410		63	
Glines	Freefall	180	Terminal		Chinook	Fingerling				94	
					Coho	Yearling	13,382	17,900		92	
Baker	Freefall to chute	240	>80	300-500	Coho	Yearling	15,000	20,000		68,79 83	Ski-jump tests
Baker	Freefall to chute	250	>80	1,850	Sockeye				-	36	
					Coho				94.7	46	
Capilano R.	Ski jump	240	Terminal	900	Coho & Steelhead	Smolt				50	
Alder Dam	Flume & freefall	26	29-49	5, 10, 15	Coho				100	97 to 100	
Mud Mtn.	Tunnel	80-120			Coho	Yearling				8.6	Based on computed recap. only
					Chinook	Fingerling				97.5	
Seton Creek	Siphon Sluiceway	25	29 (aver.)		Sockeye smolt	70-99 mm			100	98.8	
		142								92.6	
Sunset Falls	Chute	88	>70		Coho	165/lb	199,027		-	-	Good return to fishery
Ariel	Still pool	185	Terminal		Coho	50-100 mm	90	100	100	100	
Puyallup & Dungeness	Helicopter	300	Terminal		Coho	3-4 in.		299	100	99.7	Other tests made with larger fish. Tests also at 100' and 200
					Rainbow	6-7 in.		200		98.5	
Ontario	Air drop hand plant as a control	300-400	Terminal		Brook trout	15-69/lb			fing. 4.1	3.0	9-11 mo. after planting
									yearl. 6.7	3.8	2-4 mo. after planting.

velocity of 16 m/sec while falling from a tower 45 m high (Richey 1956).

Subsequent experiments showed that neither large nor small fish could sustain an impact velocity greater than 16 m/sec, when dropped into a pool. When striking velocities exceed 16 m/sec, damage begins to occur to gills, eyes and internal organs. Regenthal (from data presented in Bell and DeLacy 1972) dropped rainbow trout from a helicopter 30.5, 61 and 91.5 metres into a hatchery pond. The results were as follows:

Size of fish (cm)	Percentage survival (No. of fish) 30.5-m drop	61-m drop	91.5-m drop
15-18	98.5 (200)	97.5 (199)	98.5 (200)
25-28	94.8 (194)	82.0 (189)	81.4 (189)
30-38	67.0 (6)	83.4 (6)	20.0 (5)

Sweeney and Rutherford (1981) dropped Atlantic salmon smolts in free fall from 18 m and salmon kelts (spawned-out Atlantic salmon) from 10.6 m and 18 m. Neither the smolts nor kelts suffered any significant immediate mortality, but during an 8-day holding period, the kelts suffered a 12.5% (1 grilse and 1 older salmon) delayed mortality from the 18-m drop. The kelts used in the tests were composed of 8 grilse (mean length 50 cm) and 5 large salmon (mean length 79 cm). After the 10.6-m drop, the kelts (5 grilse and 6 older salmon) were held for 13 days with no delayed mortality.

It appears that the terminal velocity of fish smaller than about 18 cm is less than the lethal impact velocity. Fish present a very rough profile in free fall due to their contortions (Richey 1956). Since the weight goes up as the cube of a length dimension, but the drag only as the square, larger fish have a higher terminal velocity that reaches the lethal point when fish reach a length of about 18 cm.

Bell and DeLacy (1972) conclude that survival rates of fish entering a pool in a column of water, decelerating with the jet and without mechanical deflection, may equal survival under best free-fall conditions. Shearing effects, resulting from differences in velocity flow planes causing rapid acceleration or deceleration, may cause similar injuries as in free-fall conditions. High-speed cameras have revealed damage occurring to juvenile salmon coming into contact with water moving in excess of 9 m/sec (Groves 1972). Thus, injury occurs from mechanical forces due to the difference in the movement of a fish, as an object, relative to the velocity of the surrounding water mass. Injuries can occur in one millisecond and in an area 2.5 cm square. This suggests fish can be injured in any high-energy flow situation where momentary localized points of sharp velocity differences occur. Such situations would be difficult to assess or pinpoint in specific field conditions, and impossible for fish to detect or avoid.

Johnson (1970) described experiments to determine whether fingerling salmon are injured by shear forces as they are carried into a stillwater by a jet of water with a velocity of 17.5 m/sec. Fingerling coho salmon, 18-20 cm long, were introduced into a 15-cm nozzle by way of a locking system and then jetted into a pool of water. Movies of these tests indicated that although some fish were subjected to violent body distortions when breaking out of the jet, they did not suffer any apparent harm. No mortality was observed during the tests or during a seven-day holding period. Further testing using a 10-cm nozzle and a jet velocity of 20.3 m/sec demonstrated 0%-5.4% mortality. It was concluded that 20.3 m/sec was near the threshold of critical velocity that would cause mortality to smolts 18-20 cm in length.

Subsequent tests (Johnson 1972) with jet velocities of 17.5, 20.3, 23.5 and 28 m/sec produced 0%, 2.4%, 7.2% and 31% average mortality rates under experimental conditions with salmon and steelhead fingerlings. From these tests, it is concluded that velocities exceeding about 20 m/sec can cause injury and that the mortality rate rises sharply after velocities reach about 24 m/sec.

Conditions created by jets are sufficiently different from those created under free fall that the apparent differences in results do not appear to be in conflict.

Recent studies conducted at Anti Dam on East River, Sheet Harbour, Nova Scotia, showed that Atlantic salmon smolts did not suffer significant injury or delay in passing this 5-m-high storage dam. It was feared that they would likely be injured by the severe turbulence or by being dashed against the rough stone substrate of the gorge that was cut into bedrock immediately downstream of the spillway (White, personal communication). That no such injuries occurred indicates the difficulty of estimating potentially dangerous conditions from visual observations and the need to understand more fully the hydraulic conditions that result in fish injuries at such structures.

Some evidence suggests that fish larvae may be injured in passing over relatively low dams (3.1 m high). Water passing over a detention dam in the upper Holston River in Tennessee (Graser et al. 1979) had its fall broken by concrete-ledge energy dissipators installed to prevent scouring. Sampling above and below the dam suggested some loss of shad and catostomids. The authors noted more damage to the filiform shad larvae than to the more robust catostomids.

INCREASED EXPOSURE TO PREDATION

If spillways delay the natural migration of downstream migrants, unnatural concentrations of fish may gather in areas

of the forebay. On the Columbia and Snake rivers in the western United States, such concentrations appear to attract predators, especially squawfish (Ptychocheilus oregonensis). Although no quantifiable estimate of losses due to predation immediately above dams was found in the literature, it is believed to be considerable and important enough to warrant further study (Sims, personal communication).

Twomey (1965) reported that the construction of two hydroelectric dams on the River Lee in Ireland resulted in increased pike (Esox lucius) populations. Salmon smolts were found in 12% of net-caught pike in one year of investigation and in 17% in another year. Smolts tended to concentrate in large numbers above the dams, and predation by pike was believed to be an important cause of the decline in salmon abundance three years after dam construction.

Fish can be trapped in back-rolls below spillways, where they can become exposed to concentrations of predators. Long et al. (1968) showed that juvenile coho salmon released in the back-rolls at Ice Harbour and Lower Monumental dams, on the Snake River in Idaho, suffered a loss of 32%. Concentrations of seagulls and squawfish were observed feeding on the juvenile coho that were released in the back-roll.

TEMPERATURE CHANGES

Although a thorough review of water-temperature changes related to dam construction is beyond the scope of the present study, a few comments concerning temperature changes below spillways seem warranted.

If the reservoir above the dam stratifies due to warming of surface waters, the depth from which the spillway draws the discharge will influence downstream water temperatures. These, in turn, may result in changes in fish species or relative abundance below the dam, as populations adjust to the altered water-temperature regime. Sometimes, warming of river discharge affects spawning, rearing and migration of salmon below the spillway.

Dam tailwaters often display lags in seasonal temperature regimes and reduced diurnal and seasonal temperature extremes (Churchill 1957). These changes in normal temperature patterns may, in turn, affect fish distribution below dams. In some cases, warm-water fisheries have been substantially affected for considerable distances below large storage reservoirs (Vanicek 1967; Edwards 1978).

In some instances, cooler water discharged from below the warm epilimnion has resulted in increasing populations of valuable cold-water species, such as trout, below dams (Wiebe 1960). Selective withdrawals for discharges from Libby Dam on the Kootenai River in Montana provide near optimum temperatures for cutthroat trout (Salmo clarki lewisi) and rainbow trout (Salmo gairdneri) (Bonde 1979).

ATMOSPHERIC GAS SUPERSATURATION

Fish maintained in water supersaturated with air reach equilibrium with the gases dissolved in the water. When the fish move to areas of lower atmospheric pressure, the gases in their bodies tend to equilibrate to the atmosphere, and gas bubbles form under the skin, in the fins, tail, mouth and in the vascular system, causing gas embolism and death. The partial pressure of nitrogen in tissue is far greater than that of other gases (such as oxygen) and accounts for the significant amounts of nitrogen involved in the production of gas emboli (Nimms 1951). Regardless of gas composition, gas-bubble disease cannot occur unless the total dissolved gas pressure (i.e., the sum of their individual tensions), exceeds all compression forces, includig the pressures of air, water, blood and tissue elasticity (Webster 1955; Anon. 1973). For a more complete review of the history, pathology, etiology and diagnosis of gas-bubble disease in fish, the reader is referred to Weitkamp and Katz (1973 and 1977) and to Wolke et al. (1975).

Nitrogen can cause gas-bubble disease in juvenile salmonids at about 110% air saturation (Harvey and Cooper 1962). Carbon dioxide does not cause gas-bubble disease, and oxygen must be at about 350% saturation before it can cause gas-bubble disease (Rucker 1972). Water in the natural environment may become supersaturated by air entrapment, by changes in temperature and pressure, and by biotic metabolism. In terms of inflicting mortality to fish, air entrapment is the most common cause of supersaturation.

Gas-bubble disease has been reported in shad (Alosa sapidissima) by Bouck et al. (1976); in squawfish (Ptychocheilus oregonensis) by Bentley and Raymond (1976); in black bullhead (Ictalurus melas) by Fickeisen et al. (1976); in menhaden (Brevoortia tyrannus) by Clay et al. (1976); and in mountain whitefish (Prosopium williamsoni), cutthroat trout (Salmo clarki), largescale sucker (Catostomus macrocheilus) and torrent sculpin (Cottus rhotheus) by Fickeisen and Montgomery (1978), when total gas-saturation levels ranged between 120% and 135%.

The effects of various levels of supersaturated water on some freshwater aquatic invertebrates were reported by Nebeker et al. (1976). Stoneflies and crayfish were tolerant of supersaturation levels of 125%. Crayfish died at 150% saturation, with some deaths and sublethal stress signs occurring at 130% saturation. Stoneflies were immobilized at 135% and exhibited buoyancy problems at 125%, but were unaffected at 115%. Daphnia were

killed at 120% and exhibited some mortality at 115%.

Gas-bubble disease has been reported in supersaturated river water below natural falls with plunge basins (Lindroth 1957; Harvey and Cooper 1962; Westgard 1964). More frequently, air entrapment occurs at hyroelectric dams, where cascading water drives captured air to a depth sufficient to result in a solubility within the water greater than that at normal atmospheric pressure (Ebel 1969 and 1971; Beininger and Ebel 1970; Johnsen and Dawley 1974; Meekin and Allen 1974; Churchill 1979).

In the Columbia River system, supersaturated water tends to remain supersaturated because it runs in the deeper regions of the river and is recharged at subsequent spillways (Ebel 1969; Beininger and Ebel 1970; Smith 1973). Air entrapment may also occur within turbines, when air is allowed to enter the turbine to reduce negative pressures associated with lowered water flow (MacDonald and Hyatt 1973). Under normal operating conditions, the passage of water through turbines does not increase concentration of dissolved nitrogen (Lindroth 1957; Ebel 1969).

Dawley and Ebel (1975), in laboratory tests with dissolved nitrogen and argon gas concentrations ranging from 100% to 125% of saturation, found that mortality in juvenile chinook salmon and steelhead trout commenced at 115% saturation of nitrogen and argon (111% saturation of total dissolved atmospheric-gas pressure). Over 50% mortality in both species occurred in less than 1.5 days in water at 120% of saturation. At this concentration, all exposed fish died in less than three days. At concentrations of 110% dissolved nitrogen (106% total atmospheric gas), swimming ability and growth rate were affected in exposure tests of 35 days duration. Bioassays were conducted in shallow tanks (25 cm deep), with a water temperature of 15°C.

Experiments to study the benefit that fish might receive by sounding into deeper water were conducted in deep (2.5-m) and shallow (0.25-m) tanks by Dawley et al. (1975). Results showed that chinook and steelhead juveniles survived better, particularly at the lower levels of supersaturation, in the deep tanks where they could take advantage of hydrostatic compensation. Substantial mortality (50%-100%) still occurred in fish tested in deep tanks when the nitrogen concentrations exceeded 120%. It is apparent from this study, and from similar field studies, that depth of migration or hydrostatic pressure must be considered when estimating potential losses from supersaturated nitrogen for naturally migrating juvenile salmon.

In late May and early June, 1978, a major kill (upwards of 400,000) of gizzard shad, Dorosoma cepedianum, occurred downstream of the Harry S. Truman Dam on the Osage River, Missouri. Investigation revealed that it was due to gas-bubble disease. The gas saturation level in the water below the spillway was 135%. In December, 1978, concrete deflectors, called "flip-lips", were installed on the downstream face of the spillway to reduce the deep, plunging action of the spillway flows that had resulted in gas supersaturation (Churchill 1979).

In the Columbia River system, juvenile salmonids were seriously endangered by gas-bubble disease. The severity of the disease and its consequences depended on the level of supersaturation, duration of exposure, water temperature, general physical condition of the migrants and the swimming depth maintained by the fish. Ebel et al. (1975) summarize the data provided by both laboratory and field investigations conducted over several years. The following main conclusions concerning the effects of nitrogen supersaturation on downstream migrants were reached:

1. Supersaturation of atmospheric gas has exceeded 130% over long stretches of the Columbia and Snake rivers during the spring of several years since 1968.

2. Juvenile salmonid migrants confined to shallow water (1 m) suffer substantial mortality at 115% total dissolved-gas saturation after 25 days exposure.

3. Juvenile migrants allowed the option to sound and obtain hydrostatic compensation, either in the laboratory or in the field, still suffered substantial mortality after more than 20 days exposure, when saturation levels exceeded 120%.

4. On the basis of survival estimates made in the Snake and Columbia rivers, juvenile-fish losses ranging from 40% to 95% occurred; and a major portion of this mortality was attributed to supersaturation of atmospheric gases during years of high flow.

5. Juvenile salmonids subjected to sublethal periods of exposure to supersaturation recover fully when returned to normally saturated water.

Weitkamp and Katz (1977) reported field studies that indicated most juvenile salmonids in the mainstem Columbia River were found in waters of sufficient depth for hydrostatic pressure to compensate for 120% total dissolved gas pressure. Unfortunately, upstream migrating adult salmon must surface when passing over dams, thus decompressing and subjecting themselves to conditions favouring gas-bubble disease.

A shift in relative species composition of Kootenai River fish populations below Libby Dam in Montana has been attributed to the relative tolerances of mountain whitefish, largescale suckers and cutthroat trout to gas-bubble disease (Fickeisen and Montgomery 1978). Changes in relative abundance occurred immediately below the dam from approximately 50% whitefish, 50% suckers and 1% trout prior to construction of the dam to about 10% whitefish, 90% suckers and less than 1% trout after the dam was closed and gas-saturation levels exceeded 130%. Signs of gas-bubble disease were found in about 80% of the whitefish and suckers. Laboratory tests showed the following increasing order of tolerance to gas-bubble disease: mountain whitefish < cutthroat trout < large-scale sucker. Discharge was by means of sluiceways located deep in the reservoir. Water plunging through the sluices picked up air bubbles and carried them deep within the stilling basin (Bonde 1979).

Evidence regarding the ability of fishes to respond to gas supersaturation is conflicting. Some estuarine species appear to avoid water containing elevated gas tensions (Marcello and Fairbanks 1976). However, most species do not appear to respond to elevated gas tensions. Additional horizontal- and vertical-distribution data are needed for both migratory and resident species to estimate the effects on fish behaviour of varying degrees of exposure to nitrogen supersaturation. Also lacking, are studies to define synergistic and long-term sublethal effects of supersaturation.

SUBLETHAL EFFECTS

If sublethal stress is distributed throughout all members of a fish population, the effect can be catastrophic because of the way it may affect the surviving cohorts. Brett (1958), in an important paper, postulated that 10% mortality, if it represented an indiscriminate stress, might be close to the critical level, where slight additional environmental stress could result in the total loss of a fish population. Brett defined stress as a "state produced by any environmental or other factor which extends the adaptive responses of an animal beyond the normal range, or which disturbs the normal functioning to such an extent that, in either case, the chances of survival are significantly reduced".

An indiscriminate stress is one which applies to every member of the population. Examples of indiscriminate stress are high temperature, low oxygen or exposure to toxic effluents. Such stresses are not discrete in their action and spare no individual entering or inhabiting an environment with such characteristics. There are, however, differences between individuals in their ability to resist a given stress, and these resistances frequently are normally distributed throughout the population. Thus, even a stress involving a small percentage loss means that the balance of the populations are suffering though surviving.

If passage over spillways represented an indiscriminate stress to exposed fish populations, the significance of Brett's hypothesis could be serious. Consideration of this point suggests that fish passage over or through spillways does not represent an indiscriminate stress and fish that survive do not have their chances for subsequent survival reduced. An examination of mortality rates of downstream migrants at successive dams on the Columbia River does not suggest increased susceptibility to fish subjected to either spillway or turbine passage (Sims, personal communication). Hamilton and Andrew (1954) found that the number of returning adults at the Baker Dam reflected the mortalities that were recorded on the downstream migrants at the dam. If immediate spillway mortality represented a measure of indiscriminate stress, one would expect some increase in mortality between immediate and delayed estimates.

The nature of injuries caused by passage over or through spillways suggests that they represent primarily a discriminate stress, involving a variety of physically induced injuries described earlier. The problems associated with temperature changes and nitrogen supersaturation, however, are classical examples of indiscriminate stress. All members of the exposed fish population suffer, and subsequent stress could result in increased mortality.

Other sublethal effects may be caused by spillways, although no studies directly investigating this problem were found. It is known that passage over some spillways causes fish to lose their scales. Berg (1977) presents data that indicate scale loss from handling Atlantic salmon smolts affected their ability to adjust to salt water. Long et al. (1977) showed that scale loss and handling stress increased the likelihood of subsequent disease in Columbia River chinook salmon and steelhead smolts. Bouck and Smith (1979) showed that considerable seawater mortality (50%) occurred in coho salmon smolts with a 10% scale loss. Mortality was highest when scales were removed from the area of the rib cage. Recovery of smolts occurred rapidly in freshwater from a loss of scales that would be lethal in sea water (28 ppt), with 90% of the fish regaining tolerance to sea water after one post-injury day in fresh water.

STRANDING BELOW SPILLWAYS

It is beyond the scope of this report to review the subject of flow releases below dams for maintaining suitable habitat for fish and other aquatic organisms. Recent attention has focused on this problem and an exhaustive treatment of the subject is provided by Orsborn and Allman (1976). It is important, however, to

recognize that fish can be stranded and die due to dewatering below spillways when gates are suddenly closed. Kubicek (1979) describes how the rate of change in spill releases below a hydroelectric diversion dam was reduced to prevent stranding of trout in a California stream.

MEASURES FOR REDUCING MORTALITIES

Research has been undertaken in the western United States and, to a lesser extent, in British Columbia, the Maritimes and Newfoundland, to eliminate or reduce fish mortalities associated with spillways. Programs began in earnest in the early 1950s in response to serious juvenile-salmon losses associated with large-scale hydroelectric development. The rapid acceleration of hydroelectric development on the Columbia and Snake rivers in the past decade has impounded most of the free-flowing sections of these rivers. An extensive, ongoing research effort exists on these rivers to provide safe downstream passage for millions of juvenile salmonid fishes that must reach the sea to complete their life cycle. In the following sections, a brief review is presented of several techniques developed to minimize fish losses at spillways.

PREVENTION OF ENTRAINMENT

Although effort is presently underway to screen fish from a portion of turbine intakes at dams on the Columbia and Snake rivers (Montreal Engineering Company, Limited 1980), no incidents of direct screening to prevent fish entrainment at spillways was found during the course of the present study. At most low-head dams (less than about 30 m), spillways are not considered to be a serious cause of injury to downstream migrants, and considerable effort is expended to encourage them to use the spillway route rather than pass through the turbines. Although no direct screening of spillways to prevent fish entrainment is currently practised, other techniques have been developed to reduce the number of fish passing over high spillways. These are described below.

Interception and Transfer

One practical way to reduce losses of juvenile salmonids during their downstream migration past multiple dams is to collect them in upriver areas and transport them to the estuary. Fish can be intercepted above or at the upstream dam and transported by specially designed tank trucks, or by barges, to a release point below the lowermost dam. Since 1970, the U.S. National Marine Fisheries Service has transported juvenile chinook salmon and steelhead trout on the Columbia River system from the Little Goose Dam to below the Bonneville Dam. Survival rates of both were increased, compared to those of juveniles allowed to descend normally past seven consecutive dams located on their downstream migration route. The survival rates for transported fish ranged from 1.6 to 22 times as high as for the control fish (Collins et al. 1975). The homing ability of adults was not diminished nor was any change in adult age or size noted (Ebel 1978).

The fish are collected at upstream dams on the Columbia and Snake rivers by means of screening part of the flow of turbine intakes (Farr 1974; Kroma et al. 1978, 1980) and by dip netting the turbine gatewells (Bentley and Raymond 1968). For a more complete description of fish-collection techniques at turbine intakes and at gatewells, the reader is referred to Montreal Engineering Company, Limited (1979) and Ruggles (1980).

Although survival was dramatically increased in transported fish compared to non-transported controls, delayed mortality occurred immediately after truck transport. Even after streamlining methods of handling and several improvements in truck transport design, excessive delayed mortality of chinook salmon smolts continued (Long et al. 1977). These results led to consideration of the use of salt water to reduce mortality of salmon and steelhead during handling and transport.

Several investigators had shown that the addition of NaCl to water containing anadromous fish during transport increased their survival (Sykes 1950; Collins and Hulsey 1963; Chittenden 1971; Wedemeyer 1972). Long et al. (1977) found that salt (NaCl) at between 5 ppt and 15 ppt was effective in stress mitigation and for fungus (Saprolegnia) control. The latter was identified as a major cause of delayed mortality if descaling occurred. Salinities should not be allowed to go much above 15 ppt when scale loss amounts to 10% of the body surface because of possible osmotic stress (Bouck and Smith 1979).

Interception and transportation of juvenile salmon on the Columbia and Snake rivers is still viewed by fisheries agencies as an interim measure until other means of fish passage can be provided (Washington State Department of Ecology 1980).

Artificial Outlets

In the western United States, the creation of artificial discharges at hydroelectric dams, by employing pump-induced flows into simulated lake or reservoir outlets, has been utilized with varying degrees of success for passing downstream migrants. A flow from 1.4 m to 11.3 m /sec is drawn into the facility and passed through a horizontal inclined screen or through a vertical travelling screen set at an angle to the flow. Fish are removed by the screens and transported by a small bypass flow into a sump or pipe for transport to waters downstream of the dam. These devices, known as "skimmers", have captured up to 75% of the downstream

migrants passing the site (Eicher 1970).

A variation of the fixed artificial outlet is a floating type developed by the Washington State Department of Fisheries. These devices, known as "gulpers", proved satisfactory at the high-head dam on the Baker River in Washington, where pumped flows of from 1.7 m^3 to 3.4 m^3/sec were employed. For unknown reasons, gulpers at three other locations on Washington State rivers proved disappointing in capturing a significant portion of downstream migrants (Eicher 1970).

Gatewells

Research at large dams on the Columbia River in the western United States revealed that juvenile salmonid migrants concentrate in the upper levels of turbine intakes and enter turbine gatewells in large numbers (Long 1968). The gatewells are normally used for inserting gates to seal off the flow of water to the powerhouse during dewatering procedures. Juvenile salmon and trout were collected from gatewells in large numbers by means of a specially designed dip net (Bentley and Raymond 1968). A crane lowers the net in closed position through the slot to the desired depth. The net is then opened, slowly raised to the surface, and closed again to ease its withdrawal through the gate opening. Gatewells appear to be natural collectors and during low river flows, when the entire river passes through the powerhouse, up to 17% of the seaward migrants enter the gatewells on their own volition (Ingram 1960).

Large numbers of migrants entering the gatewells via the turbine intakes may become trapped unless they sound and pass out through the turbines or are collected by means of the dip-net technique described above. As a result, work is in progress to determine the most effective means of passing fish from a turbine intake gatewell by means of submerged orifices leading to adjoining trash sluiceways (Liscom 1971). Long (personal communication) reports that all the dams on the Columbia River, except Bonneville, have orifices installed in the gatewells to allow fish safe downstream passage by way of trash and ice sluiceways or by special fish-bypass systems.

Fish-passage efficiency of submerged orifices in gatewells may be reduced by the presence of a fish-guiding device in the turbine intake (Long et al. 1977). The fish-guiding device increases the flow of water through the gatewell and the associated turbulence results in descaling of fish and reduced fish-passage efficiency of the orifices. Research is continuing into orifice design and operational characteristics that will increase efficiency in passing downstream migrants out of gatewells and into a bypass system. Recent experimental work with air-lift pumps show some promise in removing fish from gatewells.

On the Saint John River, New Brunswick, downstream-migrating Atlantic salmon have been collected from the gatewells at one of the hydroelectric dams, even during periods when a large portion of the flow was by way of the spillway (Rugglen 1981).

Surface Discharge Other Than Spillways

In several instances, downstream-migrating, juvenile Pacific and Atlantic salmon have been observed leaving the forebay areas by means of surface discharges through trash gates or other facilities designed for surface spills. Farwell (1972) describes two hydroelectrical installations on the Exploits River in Newfoundland, one having such an exit and the other not. He describes differences in fish accumulation in the forebays of these two sites and concludes that this type of exit could replace costly fish-diversion works. Observations from this study suggested that Atlantic salmon smolts were migrating close to the surface and were attracted to the funnelling of the surface flow toward a gate located inside and at the downstream end of the forebay. Fish are conducted to the tailwater by means of a wooden fishway, leading from the surface spillgate and descending with an overall slope of 1 in 4.5 to the river below (Davis and Farwell 1975).

At the Dalles Dam on the Columbia River, about 65% of the downstream-migrant salmonids are attracted to the ice and trash sluiceway. A total water flow of about 68 m^3/sec is passed through two sluiceway gates. The choice of which gate to use was determined by releasing marked fish about 5 km upstream and recovering a portion of them in a recovery net located near the downstream end of the ice and trash sluiceway. Work is still in progress to develop the most effective procedure for passing the maximum number of migrants during periods when most of the flow is by way of the turbines.

Semple and McLeod (1976) described a floating-screen deflector, which guided alewives and Atlantic salmon to a bypass discharge through a vacant draft-tube opening. Tests with marked, hatchery-reared, salmon smolts showed the deflector guided up to 72% of the fish released in the forebay. Nearly 50% of the smolts used the bypass without screening provisions.

A similar device leads downstream-migrating Atlantic salmon to a surface discharge adjacent to the powerhouse intakes at the Malay Falls hydroelectric dam on the East River, Sheet Harbour, Nova Scotia. An automatic-weir control gate provides about 340 litres/sec flow to a semi-circular, fibreglass flume designed to carry fish to the tailrace (Resource Development Branch 1975). The device had an average bypass efficiency of 52% for Atlantic salmon smolts without fish-

deflector screens (Semple 1979). The deflector did not improve the bypass efficiency for salmon smolts.

Schoeneman (1959) describes an open flume made of 61-cm-diameter, half-section, galvanized sheet-metal pipe, 124 metres long, declined 22 degrees, at the Alder Dam on the Nisqually River in Washington State. The total drop in the flume was approximately 43 metres, with an additional free-fall drop of eight metres into the pool below the dam. Fish were observed to fall free from discharge of 142, 284 and 426 litres per second, which were the discharges through the flume during the tests. Survival of 8 cm-10 cm coho salmon fingerlings was 97% and was not influenced by the volume of water flowing down the flume, at least within the limits tested. Maximum velocity in the flume was 15 m/sec.

Experiments on the Baker River demonstrated that fish in the bypass system were being injured when entering the downstream pool with the added velocity of the water column that carried them. This bypass flow was transported by means of a pipe placed diagnonally on the downstream face of the dam and ending about 49 metres above the tailwater. Mortalities were eliminated when the exit flow was reduced by adjustments at the discharge end of the pipeline, so that the fish were allowed to fall free into the tailwater pool (Bell and DeLacy 1972).

The exact factors affecting the attraction of downstream migrants to outlets at existing dams are not known, and it is difficult to generalize about the best locations for the placement of fish outlets. The behaviours of fish species differ. For instance, the majority of sockeye and coho yearlings were observed to migrate in the top 4.5 metres of Baker Reservoir in Washington State. Consequently, an experiment was conducted to determine the guiding efficiency of a webbing barrier 4.5 metres deep and 73 metres long, angled across the forebay to a surface bypass trap. Sockeye showed a greater tendency to sound under the barrier than did coho (Rees 1957). Almost no information concerning non-salmonid species could be found in the literature concerning their behaviour at spillways, and specific studies are required before an understanding of how these fish react to spillways can be reached. More precise studies to determine the behaviour of fish approaching the spillways offer promise of providing valuable information for subsequent design of effective fish-bypass facilities.

Fish distribution in the reservoir may be a determining factor in the success of surface bypasses. For instance, Burner (1949) found that downstream-migrant salmon were distributed throughout the 18 metres of depth in the foreby of Bonneville Dam. Small surface bypasses on this dam have been ineffectual in passing significant numbers of migrants (Arndt, personal communication).

Flow Control

Because reservoirs delay the rate of downstream migration of juvenile salmonids and because reductions in spillway flows result in more downstream migrants being exposed to turbine-induced mortality, controlled flows have been used to reduce fish mortality resulting from hydroelectric development. The idea is to operate dams sequentially, in a way that provides more favourable flows during the period of peak downstream migration. Higher rates of flow result in less delay in the reservoirs (Raleigh and Ebel 1967; Raymond and Sims 1980) and in a smaller proportion of the migrants being exposed to the effects of the turbines. In other words, efforts are made to increase the entrainment of fish into flows over or through spillways. In some cases, a sequential shutdown of individual turbines is used to guide migrants to a location where a spillway is opened as the last turbine is shut down, thus drawing the migrants to and over the spillway. The provision of spill to pass fish is the best alternative available to protect downstream migrants in the Columbia River (Washington State Department of Ecology 1980).

A committee was established to recommend minimum flows in the Snake and Columbia rivers to provide more favourable conditions for downstream migration of salmon and steelhead (Collins et al. 1975). Labelled "Operation Fish-Flow", the program took into account the needs of both fish and energy demands. Flow control in 1977 proved successful in reducing the migration time through reservoirs in the mid-Columbia River and increased the survival of chinook salmon smolts and fry (Sims 1978). "Operation Fish-Flow" was also believed partly responsible for the relatively high survival of Snake River steelhead smolts during their 1975 migration. Survival of steelhead during their migration from the Lower Granite Dam on the Snake River to the Dalles Dam on the Columbia River (encompassing about 240 kilometres and seven dams) was the highest measured since 1969 (Raymond 1979).

SPILLWAY DESIGN

Ski-Jump Spillways

Experiments with "ski-jump" spillways (where the column of water falls free into the pool below) have been successful in eliminating injuries caused to fish by striking the face of the dam and being scraped along its face under normal spillway conditions (Regenthal 1957; Gunsolus and Eicher 1970). If fish fall free from the column of water from which they started the spill, conditions for survival are usually improved. On the other hand, fish that are accelerated within the water column and subjected to tumbling and shearing forces within the water usually exhibit low survival rates (Bell and DeLacy 1972).

The advantage of the ski-jump design is that abrasion on a spillway face is eliminated. No information is available, however, on the size of the cushioning pool required for specific heights or discharges. High mortality of 70% at the ski-jump spillway at Cleveland Dam on the Capilano River was considered to be caused by the effects of excessive turbulence and abrasion in the relatively shallow pool at its base (Vernon and Hourston 1957). In some instances, wind has blown migrants onto the face of the dam, thus increasing mortality. It seems likely that the ski-jump spillway provides a means of reducing but not eliminating mortalities. Whether this technique would have any advantages over flumes or pipes for passing downstream migrants from by-pass collection systems to tailwater is questionable.

Provision of a ski-jump-type spillway on the Lower Baker Dam gave downstream migrants a free fall into the pool below and eliminated injuries caused by striking the face of the dam. As a result, this design has been used at many high spillways in the western United States - notably at Pelton, North Fork, Mayfield, Brownlee, Ox Bow, Hells Canyon and Upper Baker (Eicher 1970).

Flow Deflectors

Recent emphasis on spillway design has focused on attempting to reduce the deep plunging action responsible for air entrainment and subsequent nitrogen supersaturation. This became a serious problem in the Columbia River system, where a series of dams created large areas of water supersaturated with atmospheric gases to levels that were lethal to fish. In order to reduce the severity of the problem, early considerations involved the installation of additional turbines, increased storage capacity to control flow, use of slotted bulkheads in vacant turbine intakes and the installation of spillway flow deflectors to reduce air entrainment during spilling (Smith 1973). The latter method appears to be the most practical and direct.

Long et al. (1972) describe early experiments where perforated bulkheads were used in intakes of empty turbine bays at Lower Monumental Dam on the Snake River. Although the perforated bulkheads allowed water to pass through with little increase in dissolved nitrogen levels, mortality to juvenile chinook and coho salmon was too high (about 50%) to permit their use. Significant numbers of migrants were believed killed after passage through the jet stream from the perforated bulkhead. Extreme turbulence and counter currents in the empty generator bay resulted in fish being forced against steel reinforcement bars and into repeated contact with the bulkhead jet stream.

Subsequent studies (Long et al. 1975) indicated that these bulkheads could be installed upstream from an operating turbine without increasing the mortality of descending fish. Placement of slotted bulkheads in front of an operating turbine allowed hydroelectric projects to pass extra water through unloaded turbine units during the spring freshet when power demand was not sufficient to fully load all turbines. The use of perforated bulkheads, however, does not appear to offer a satisfactory solution to the supersaturation problems on the Columbia River, but spillway deflectors have proven to be effective.

Spillway deflectors are concrete sills placed near the base of the spillway. Essentially, the deflector is an addition to the spillway ogee that changes the direction of spilling water from plunging to horizontal, thus reducing the pressure gradient that forces atmospheric gases into solution (Fig. 1). After three years of testing, Long et al. (1975) concluded that flow deflectors were a promising method to reduce gas supersaturation at spillways. The 1975 studies conducted at Lower Monumental Dam indicated mortality of steelhead smolts was lower when they descended through spillways equipped with flow deflectors (2.2%) than through standard spillways (25.5%).

Spillway flow deflectors were recommended for Little Goose, Ice Harbour, McNary and Bonneville dams (Ebel et al. 1975). As a direct result of their success on the Columbia and Snake River dams, they were also installed on the Harry S. Truman Dam on the Osage River, Missouri (Churchill 1979).

ARTIFICIAL PROPAGATION

In recent years, artificial propagation, largely by means of fish hatcheries and artificial spawning channels, has proven to be an effective fishery-management tool. For example, artificial production accounts for over 50% of all adult salmon and steelhead returning to the Columbia River system (Washington State Department of Ecology 1980). The heavy reliance on hatchery production, however, raises several questions about the effect hatchery stocks might have on wild stocks. Differing rates of production (Ricker 1973) between hatchery and wild stocks create potentially serious problems when these stocks are harvested in mixed-stock fisheries. The less productive wild stocks may be harvested too heavily, in order to adequately harvest the more productive hatchery stock. Concern has also been expressed about the dilution of wild gene pools by hatchery fish spawning with wild stock and the possibility of disease introduction from hatchery-produced fish.

In cases where no suitable technology exists to prevent mortality of fish passing over high spillways, then artificial propagation of either all or a portion of the anadromous fish run might represent an effective solution. For example, the

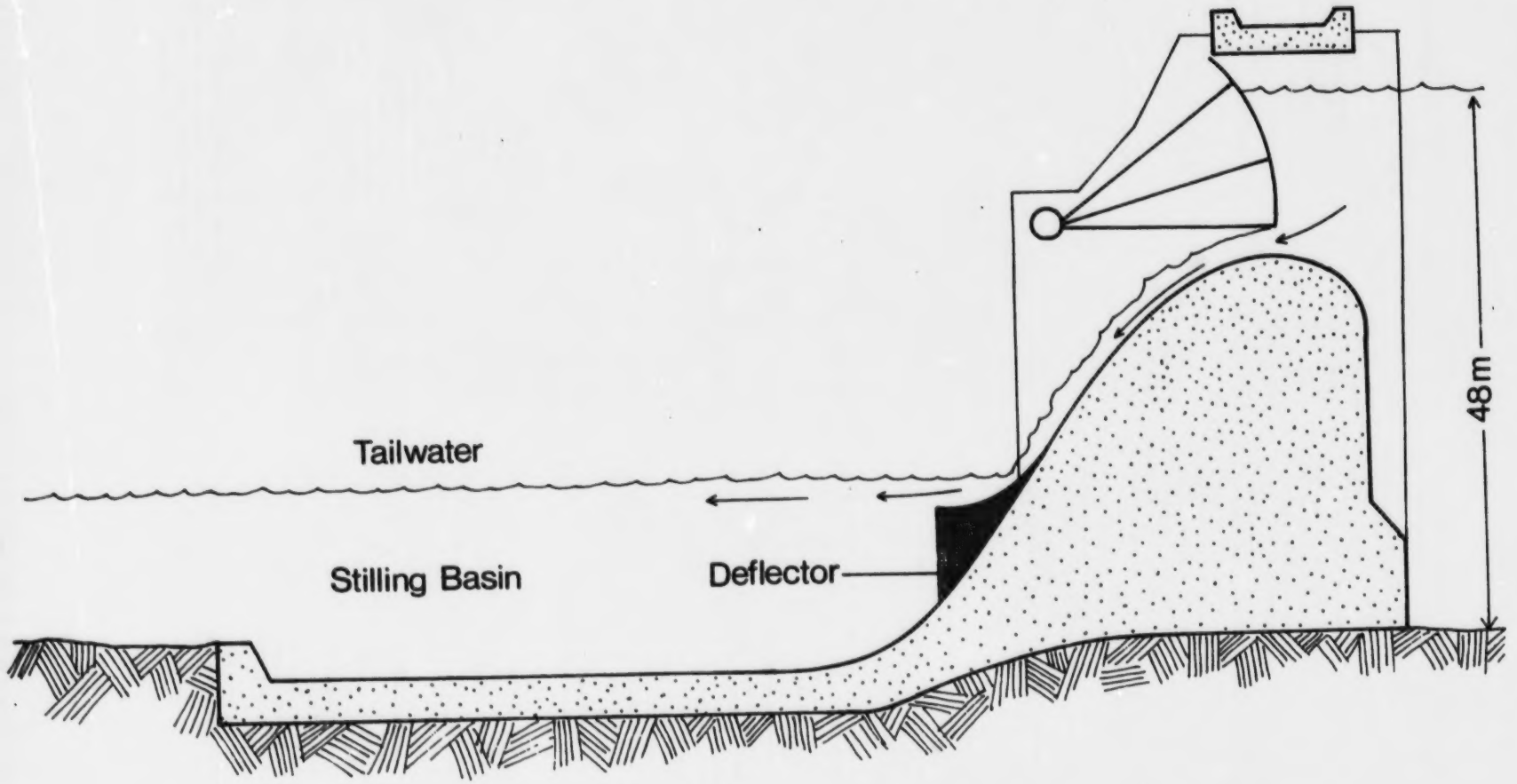

FIG. 1. Spillway flow deflector (adapted from Smith 1973)

Capilano River Hatchery, located in Vancouver, British Columbia, successfully mitigated the decrease in coho and steelhead stocks resulting from construction of the Cleveland Dam. Another example is the Mactaquac Hatchery on the Saint John River, New Brunswick. This hatchery supplements natural Atlantic salmon smolt production, which was adversely affected by habitat destruction and turbine mortality. Sometimes artificial propagation may represent the only solution available to mitigate losses of fish caused by dams.

SPILLWAY AND STILLING-BASIN HYDRAULICS

All storage dams must be protected by spillways. Their purpose is to discharge the excess river flow, in such a manner as to insure the safety of the dam and appurtenant works at all times. The type of spillway used in a given situation depends upon the kind of dam, the nature of its foundation, the magnitude of the spillway discharge and the topography.

Regardless of the type, every spillway has three basiç components - a crest section, a conveyance section and a discharge section. The crest section is the inlet to the spillway. From the crest, the flow must be conveyed in a chute or tunnel to a level near the natural river level on the downstream side of the dam. The spillway terminates in a discharge section, from which the flow reenters the channel. If necessary, the discharge section may also be the means of dissipating the excess kinetic energy of the flow.

Spillways are ordinarily classified according to their most prominent feature, either as it pertains to the control, to the discharge channel, or to some other component. They often are referred to as controlled or uncontrolled, depending on whether they are gated or ungated. Commonly referred to types are the free-overfall (straight-drop), ogee (overflow), side-channel, open-channel (chute), conduit (tunnel), drop-inlet (shaft) and siphon spillways. A brief description of each is given below.

FREE-OVERFALL OR STRAIGHT-DROP SPILLWAY

A free-overfall or straight-drop spillway (Fig. 2) is one in which the flow drops freely from the crest. Scour and a deep plunge pool will occur at the base of the overfall where no artificial protection is provided. The volume and depth of the pool are related to the range of discharges, the height of the drop, the depth of tailwater, and the composition of the riverbed.

If tailwater depths are sufficient, a hydraulic jump will form when a free-overfall jet falls upon a flat apron. Hydraulic jump is an abrupt rise (a standing wave) in the water surface when water at high velocity discharges into a zone of lower velocity. Flow over the control ordinarily is free discharging; air is admitted to the underside of the nappe (see Fig. 2) to avoid the jet being depressed by reduced underneath pressure. Dissipation of the flow in the downstream basin may be obtained by the hydraulic jump or by impact and turbulence induced in a basin with impact blocks.

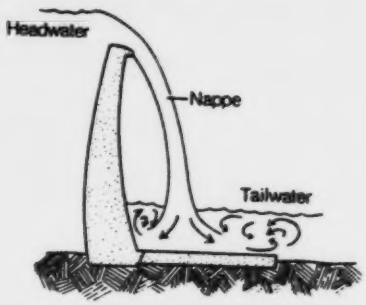

FIG. 2. Typical free-overfall spillway

The jump characteristics of the straight-drop basin are similar to those for other jump basins. Where tailwater depths are greater than the conjugate depth (depth required to create a hydraulic jump), the jump will move back on the falling nappe, raising the depth of the under-nappe pool. With greater depths of the under-nappe pool, the nappe will not plunge immediately to the floor of the basin but will be deflected upward.

The dissipation of the high energy in an impact-block basin is principally by turbulence induced by the striking of the incoming flow upon the impact blocks. The impact-block basin is considerably smaller than the hydraulic-jump basin, as the hydraulic forces are more concentrated.

The critical parameters of free-overfall spillways related to fish mortality are the height of drop, concentration of flow and depth of tailwater.

OGEE SPILLWAY

The ogee spillway (Fig. 3) has a control weir which is ogee or S-shaped in profile. The upper curve of the ogee

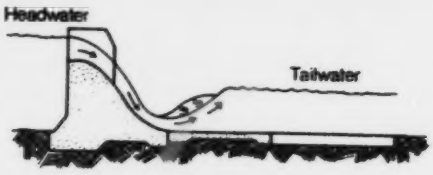

FIG. 3. Typical ogee spillway

ordinarily is made to conform closely to the profile of the lower face of the nappe of a ventilated sheet falling from a sharp-crested weir. Flow over the crest is made to adhere to the face of the profile by preventing access of air to the underside of the sheet. For discharges at design head, the flow glides over the crest with no interference from the boundary surface and attains near maximum discharge efficiency. A reverse curve at the bottom of the slope turns the flow onto the apron of a stilling basin or into the spillway discharge channel.

The critical parameters of ogee spillways related to fish mortality are mainly a function of the type of conveyance structure and type of energy-dissipation facility utilized for the structure.

SIDE-CHANNEL SPILLWAY

The side-channel spillway (Fig. 4) is one in which the control weir is placed along the side of, and approximately parallel to, the upper portion of the spillway discharge channel. Flow over the crest falls into a narrow trough opposite the weir, turns an approximate right angle, and then continues into the main discharge channel. The theory of flow in a side-channel spillway is based principally on the law of conservation of linear momentum, assuming that the only forces producing motion in the channel result from the fall in the water surface in the direction of the axis.

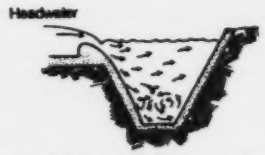

FIG. 4. Typical side-channel spillway (side channel in cross section)

This premise assumes that the entire energy of the flow over the crest is dissipated through its intermingling with the channel flow and is therefore of no assistance in moving the water along the channel. Axial velocity is produced only after the incoming water particles join the channel stream.

The critical parameters of side-channel spillways related to fish mortality are the concentration of flow, type of conveyance structure and type of energy-dissipation facility utilized for the structure.

CHUTE SPILLWAY

A spillway whose discharge is conveyed from the reservoir to the downstream river level through an open channel, placed either along a dam abutment or through a saddle, might be called a chute, open-channel, or trough-type spillway (Fig. 5). A spillway having a chute-type discharge channel, though controlled by an overflow crest, a gated orifice, a side-channel crest, or some other control device, may still be called a chute spillway. Chute spillways ordinarily consist of an entrance channel, a control structure, a discharge channel, a terminal structure and an outlet channel. The simplest form of chute spillway has a straight centerline and is of uniform width. Often, either the axis of the entrance channel or that of the discharge channel must be curved to fit the alignment to the topography. Flows upstream from the crest are generally at low velocity, accelerating rapidly when the water passes over the crest. Flows in the chute are ordinarily maintained at high velocities, either at constant or accelerating rates, until the terminal structure is reached. The critical parameters of chute spillways related to fish mortality are the length of chute, concentration of flow and type of energy-dissipation facility utilized for the structure.

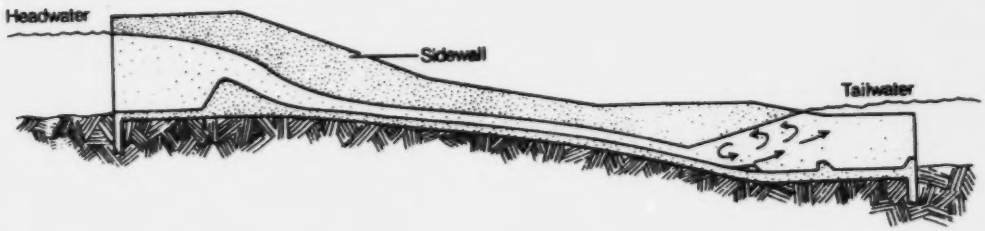

FIG. 5. Typical chute spillway

TUNNEL OR CONDUIT SPILLWAY

Where a closed channel is used to convey the discharge around or under a dam, the spillway is called a tunnel or conduit spillway (Fig. 6). The closed channel may take the form of a vertical or inclined shaft, a horizontal tunnel through earth or rock, or a conduit constructed in open cut and backfilled. Most forms of control structures, including overflow crests, vertical- or inclined-orifice entrances, drop-inlet entrances, and side-channel crests, can be used with conduit and tunnel spillways. Tunnel spillways may present advantages in narrow canyons for dam sites with steep abutments or at sites where there is danger to open channels from snow or rock slides. Conduit spillways may be appropriate at dam sites in wide valleys, where the abutments rise gradually and are at a considerable distance from the stream channel. Use of a conduit will permit the spillway to be located under the dam near the stream bed.

The critical parameters of tunnel or conduit spillways related to fish mortality are length of tunnel or conduit, concentration of flow and type of energy-dissipation facility utilized for the structure.

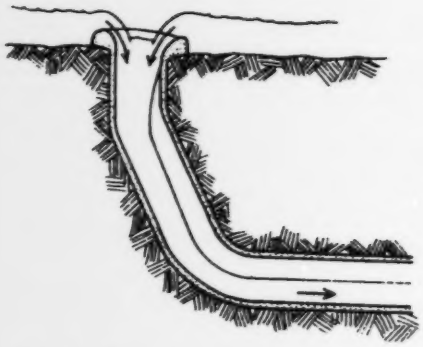

FIG. 7. Typical shaft spillway

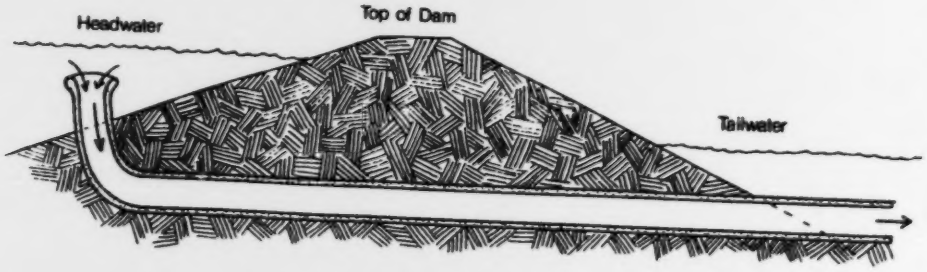

FIG. 6. Typical conduit spillway

SHAFT SPILLWAY

A drop-inlet or shaft spillway (Fig. 7) is one in which the water enters over a horizontally positioned lip at atmospheric pressure, drops through a vertical or sloping shaft, and then flows to the downstream river channel through a horizontal or nearly horizontal conduit or tunnel.

The critical parameters of shaft spillways related to fish mortality are length of conduit, concentration of flow and type of energy-dissipation facility utilized for the structure.

SIPHON SPILLWAY

A siphon spillway (Fig. 8) is a closed conduit system formed in the shape of an inverted U, positioned so that the inside of the bend of the upper passageway is at normal reservoir storage level as shown on the following page. The initial discharges of the spillway, as the reservoir level rises above normal, are similar to the flow over a weir. Siphonic action takes place after the air in the bend over the crest has been evacuated. Continuous flow is maintained by the suction effect due to the gravitational pull of the water in the lower leg of the siphon. Most siphon spillways are composed of five component parts.

These include an inlet, an upper leg, a throat or control section, a lower leg and an outlet. A siphon-breaker air vent is also provided to control the siphonic action of the spillway, so that it will cease operation when the reservoir water surface is drawn down to normal level.

The critical parameters of siphon

spillways related to fish mortality are length of conduit and type of energy-dissipation facility utilized for the structure.

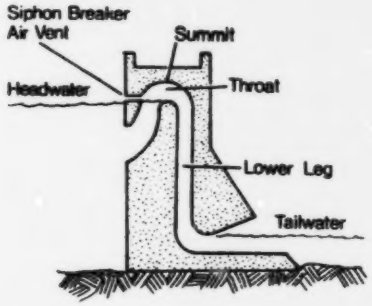

FIG. 8. Typical siphon spillway

HYDRAULICS OF TERMINAL STRUCTURES

Energy in water discharged over a conventional spillway is dissipated mainly in the turbulent pool formed at the base of the dam. The energy dissipation is intentionally confined to a relatively small volume of water at the base of the dam, where the tremendous force of the water is spent against concrete energy dissipators. This is done to reduce danger of scouring the river bed and undermining the foundation of the dam. Fish injuries and/or mortalities may occur in the spillway terminal structure where the kinetic energy of the flow is dissipated. Four types of energy-dissipating facilities are discussed below.

Deflector or Flip Buckets

Where the spillway discharge may be safely delivered directly to the river without providing a dissipating or stilling device, the jet is often projected beyond the structure by a flip or deflector bucket (Fig. 9). Flow from these deflectors leaves the structure as a free-discharging upturned jet and falls into the stream channel some distance from the end of the spillway. The path the jet assumes depends on the energy of flow available at the lip and the angle at which the jet leaves the bucket.

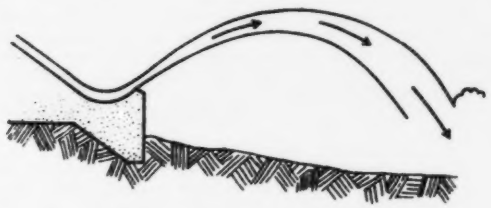

FIG. 9. Typical flip bucket

The critical parameters of deflector-bucket terminal structures related to fish mortality are height of fall, concentration of flow, jet velocity and depth of tailwater.

Hydraulic-Jump Basins

Where the energy of flow in a spillway must be dissipated before the discharge is returned to the downstream river channel, the hydraulic-jump basin (Fig. 10) is an effective device for reducing the exit velocity to a tranquil state. The jump which will occur in a stilling basin has distinctive characteristics and assumes a definite form, depending on the energy of flow which must be dissipated in relation to the depth of flow. The jump form and the flow characteristics can be related to the Froude number. Froude number is the ratio of flow velocity to wave velocity. If the Froude number is less than unity, the flow is subcritical. 'In this state the flow has a low velocity and is often described as tranquil and streaming. If the Froude number is greater than unity, the flow is supercritical. In this state the flow has a high velocity and is usually described as rapid, shooting and torrential.

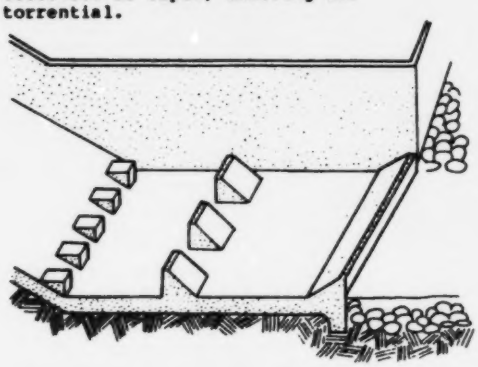

FIG. 10. Typical hydraulic-jump stilling basin

When the Froude number of the incoming flow is equal to 1.0, the flow is at critical depth and a hydraulic jump cannot form. For Froude numbers from 1.0 to about 1.7, the incoming flow is only slightly below critical depth, and the change from this low-stage to the high-stage flow is gradual and manifests itself only by a slightly ruffled water surface. As the Froude number approaches 1.7, a series of small rollers begin to develop on the surface and become more intense with increasingly higher values of the number.

Other than the surface-roller phenomena, relatively smooth flows prevail throughout the Froude-number range up to about 2.5. No special stilling basin is needed to still flows where the incoming-flow Froude number is less than 2.5. Since such flows are not attended by active turbulence, no baffles or other dissipating devices are needed.

For Froude numbers between 2.5 and 4.5, an oscillating form of jump occurs, the entering jet intermittently flowing near the bottom and then along the surface of the downstream channel. The oscillating flow causes surface waves which carry considerably beyond the end of the basin. Stilling basins to accommodate these flows are the least effective in providing satisfactory energy dissipation, since the attendant wave action ordinarily cannot be controlled by the usual basin devices. Waves generated by the flow phenomena will persist beyond the end of the basin and must often be dampened by means apart from the basin.

For the range of Froude numbers for the incoming flow between 4.5 and 9, a stable and well-balanced jump occurs. Turbulence is confined to the main body of the jump, and the water surface downstream is comparatively smooth. The installation of accessory devices such as chute blocks, baffle blocks and sills along the floor of the basin produce a stabilizing effect on the jump, which permits a shortnening of the basin and provides a factor of safety against sweep-out (loss of hydraulic jump) due to inadequate tailwater depth. This basin relies on dissipation of energy by the impact blocks and also on the turbulence of the jump phenomena for its effectiveness. As the Froude number increases above 9, the turbulence within the jump and the surface roller becomes increasingly active, resulting in a rough water surface with strong surface waves downstream from the jump.

The critical parameters of hydraulic-jump stilling basins related to fish mortality are the concentration of flow and depth of tailwater.

Submerged-Bucket Dissipators

When the tailwater depth is greater than the conjugate depth for the formation of a hydraulic jump, dissipation of the high energy of flow can be effected by the use of a submerged-bucket deflector. The hydraulic behaviour in this type of dissipator is manifested primarily by the formation of two rollers; one is on the surface moving counter-clockwise and is contained within the region above the curved bucket, and the other is a ground roller moving in a clockwise direction and is situated downstream from the bucket. The movements of the rollers, along with the intermingling of the incoming flows, effectively dissipate the high energy of the water. Two types of roller buckets have been developed (Fig. 11).

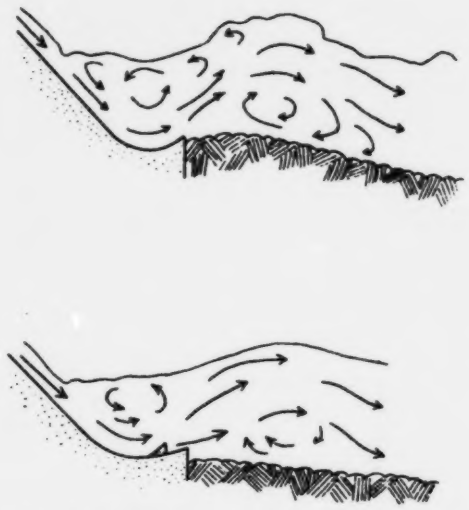

FIG. 11. Typical hydraulic action in solid- and slotted-type buckets

The high-velocity flow leaving the deflector lip of the solid bucket is directed upward. This creates a high boil on the water surface and a violent ground roller moving clockwise downstream from the bucket. This ground roller continuously pulls loose material back towards the lip of the bucket and keeps some of the intermingling material in a constant state of agitation. In addition, the more turbulent surface roughness induced by the severe surface boil carries farther down the river, causing strong eddy currents. In the slotted bucket, the high-velocity jet leaves the lip at a flatter angle, and only a part of the high-velocity flow finds its way to the surface. Thus, a less violent surface boil occurs and there is a better dissipation of flow in the region above the ground roller, which results in less concentration of high-energy flow throughout the bucket and a smoother downstream flow.

The critical parameters of submerged-bucket dissipators as related to fish mortality are concentration of flow and depth of tailwater.

Plunge Pools

When a free-falling overflow nappe drops vertically into a pool in a riverbed, a plunge pool will be scoured to a depth which is related to the height of the fall, the depth of tailwater, and the concentration of the flow. Depths of scour are influenced initially by the erodibility of the stream material or the bedrock and

by the size or the gradation of sizes of any armouring material in the pool. However, the armouring or protective surfaces of the pool will be progresively reduced by the abrading action of the churning material to a size which will be scoured out; and the ultimate scour depth will, for all practical considerations, stabilize at a limiting depth irrespective of the material size.

The critical parameters of plunge pools as related to fish mortality are height of fall, concentration of flow and depth of tailwater.

FREQUENCY OF OPERATION

The frequency of spillway use is determined by the runoff characteristics of the drainage area and by the nature of the development. Ordinarily, river flows are stored in the reservoir, diverted through head works, or released through outlets, and the spillway is not required to function. Spillway flows result during floods or periods of sustained high runoff when the capacities of other facilities are exceeded. Where large reservoir storage is provided, or where large outlet or diversion capacity is available, the spillway will be utilized infrequently. At diversion dams where storage space is limited and diversions are relatively small compared to normal river flows, the spillway will be used almost constantly.

In the case of the free or uncontrolled overflow crest, the spillway automatically releases water whenever the reservoir water surface rises above crest level. For this type of spillway, water cannot be released if the water level in the reservoir is below the crest level. Similarly, during times of spilling, the discharge is a function of the head on the crest only, and no means exist to regulate the discharge.

In the case of the gated or controlled spillway, some margin of flexibility is provided. Either lesser or greater amounts of water may be released, depending on the type of control. However, this is true only to a point. Once the water level in the reservoir reaches a certain predetermined level, flow must be released to insure the safety of the structure.

SPILLWAY FLOW AND FISH MORTALITY

In some instances, the flow of water over spillways can be modified to improve conditions that are harmful to fish. For example, "ski-jump" spillways have proven useful at high dams to prevent fish from striking the face of the dam and being scraped along its face under normal spilling conditions. In cases where nitrogen supersaturation is a problem, flow deflectors can be installed at the base of the spillway ogee to direct flow horizontally into the stilling basin, and hence reduce the deep plunging action responsible for air entrainment.

Rapid and efficient energy dissipation is desirable to avoid high water velocities downstream that might cause scouring of the stream bed. Often, hydraulic-model studies will be required to work out effective compromises between the need to rapidly dissipate energy and the need to reduce undesirable conditions for fish so that as little turbulence as practical occurs in the energy-dissipating area. The reduction of a back-roll that may trap fish below the spillway can often be achieved. The creation of streamlined flow over spillways and the reduction of conditions likely to produce cavitation will also serve to reduce the potential for fish mortality when they pass over or through spillways. Bell and DeLacy (1972) conclude that to obtain the highest survival of downstream-migrating fish, spillways should be operated for minimum turbulence, back-roll and energy dissipation.

If the general problems of spillway design are approached from the point of view of reducing the rate of dissipation of energy in the tailwater pool, designs might be developed that would improve the chances of fish survival. Means of accomplishing this include increasing the length of crest of the spillway, deepening the pool at the base of the spillway, increasing the cross-sectional area of the spill by aeration or otherwise, and dissipating the energy in stages as is done, for example, in fish ladders.

In general, conditions that are believed responsible for causing fish mortality at spillways will increase in proportion to the height of the spillway. It is unlikely that this relationship is linear, and evidence suggests that spillways less than about 30-35 metres in height need not pose a serious problem to downstream-migrating salmonids. This is not to say that all spillways less than 30 metres in height do not cause injury to fish, but rather that height in inself will not be the determining factor in fish mortality until spillways reach a height of about 35 metres. The choice of this rather arbitrary height is based on juvenile salmonid mortality studies at existing dams in western North America.

FISH MORTALITY PROBLEMS ASSOCIATED WITH SPILLWAYS IN CANADA

To assess the general nature of fish mortality problems at spillways in Canada and to identify specific current problems relative to hydroelectric development, contact was made with agencies directly responsible for the protection and management of the freshwater-fishery resource. In some instances, the information gained from these contacts was augmented by reference to information obtained during the literature-review phase of the study. The following provincial and regional assessments are based on the perception of existing and potential

problems by individuals currently responsible for protecting freshwater and anadromous fishes at spillways in Canada.

BRITISH COLUMBIA

The current assessment in British Columbia indicates that minimum flow below spillways is considered to be a much more serious problem than the mortality of fish passing over dams. Although a specific problem associated with the operation of a spillway is presently under investigation (Fretwell 1980), it is only peripheral to protecting downstream-migrant sockeye salmon from mortality inflicted by passage through hydraulic turbines. In the past, concern was expressed for fish mortality at the Cleveland Dam on the Capilano River. This problem has been overcome by augmenting natural fish production by a salmonid hatchery located downstream.

The most serious potential problem associated with spillways in several British Columbia rivers is gas supersaturation of sufficient magnitude to cause gas-bubble disease (Clark 1977). Although relatively few fish (four out of seventy examined) showed symptoms of gas-bubble disease, several rivers had total dissolved atmospheric-gas content of over 110% saturation. In reaches of the Columbia, Kootenay and Pend d'Oreille rivers, 156 readings of over 120% gas saturation were recorded (Table 2). The approximate locations, total numbers of observations and numbers of observations in each range of percentage saturation for these three rivers are presented (Table 3). It appears that the Hugh Keenleyside Dam on the Columbia River and the Corra Linn Dam on the Kootenay River cause gas supersaturation in the waters downstream of them.

ALBERTA

There is no well-documented evidence in Alberta of fish mortalities below spillways, although there are a number of power dams and irrigation reservoirs where potential problems of supersaturation could occur. There are, however, two reports of fish mortalities, below the spillway of St. Mary's Reservoir and Waterton Reservoir. These mortalities were not investigated in detail and the reports concerned primarily mountain whitefish (Prosopium williamsoni) and lake whitefish (Coregonus clupeaformis); however, the cause of death could not be identified precisely and

TABLE 2. Numbers of observations made at various ranges of percent total saturation[1] (TS) for dissolved atmospheric gases in some British Columbia water bodies (from Clark 1977).

Rule-of-thumb acceptability re gas-bubble disease in fish		Satisfactory	Borderline	Unsatisfactory	Critical
Recommended monitoring programs		Occasional spot checks	More frequent spot checks	Weeky analysis; check fish	Daily analysis; check fish
River, stream or lake	Total no. of observations	Number of observations in each range			
		< 110%	110%-120%	120%-140%	> 140%
Problem rivers (including reservoirs)					
Bull	11	6	5	0	0
Columbia	253	89	39	71	54
Duncan	23	22	1	0	0
Fraser	104	88	16	0	0
Kootenay	125	69	32	24	0
Nechako	40	34	6	0	0
Peace	43	42	1	0	0
Pend d'Oreille	30	11	12	7	0
Stave	19	18	1	0	0
Thompson	13	12	1	0	0
Miscellaneous and non-problem waters					
Streams and reservoirs	69	69	0	0	0
Lakes	20	19	1	0	0
Marine waters	6	6	0	0	0
Totals	756	485	115	102	54

[1] %N² substituted in place %TS for several dates where %TS not known.

TABLE 3. Numbers of observations made at various ranges of dissolved atmospheric gas for main reaches of Columbia, Kootenay and Pend d'Oreille rivers (modified from Clark 1977).

Rule-of-thumb acceptability re gas-bubble disease in fish		Satisfactory	Borderline	Unsatisfactory	Critical
Recommended monitoring programs		Occasional spot checks	More frequent spot checks	Weeky analysis; check fish	Daily analysis; check fish
River and location	Total no. of observations	Number of observations in each range			
		<110%	110%-120%	120%-140%	>140%
Columbia					
Above Mica Dam	5	5	0	0	0
Mica Dam to Revelstoke	25	17	8	0	0
Revelstoke to Hugh Keenleyside Dam	35	33	2	0	0
Hugh Keenleyside Dam to Castlegar Ferry	148	23	20	51	54
Castlegar Ferry to border	40	11	9	20	0
Kootenay					
Headwater to border	15	15	0	0	0
Porthill to Kootenay Lake	23	21	2	0	0
Kootenay Lake	32	26	6	0	0
Corra Linn Dam to border	55	7	24	24	0
Pend d'Oreille					
Border to Waneta	16	5	7	4	0
Waneta to Columbia	14	6	5	3	0

problems were not persistent. The two dams that form the reservoirs are 62 m and 56 m high, respectively.

In addition to the above-mentioned dams, where problems of supersaturation of nitrogen might occur, the Bassano Dam was identified as potentially problematical because of possible injuries to fishes when moving over the spillway. This 20-m-high dam is situated on the Bow River, 120 km east of Calgary.

SASKATCHEWAN

In this province, no fish mortalities in connection with spillways have been reported. Most spillway use in Saskatchewan is for short periods during spring floods. For the remainder of the year, the spillways have no flow. In some years, there is not even any spring overflow.

MANITOBA

The problems of fish mortalities associated with spillways have not been intensively examined in Manitoba. Since virtually all dams are relatively low-head structures (30 m or less), the problem of nitrogen supersaturation has not been encountered. Similarly, there are no indications that physical damage to fish passing over spillways is a significant cause of fish mortality. The only problem encountered in this province is one which occurred at the Grand Rapids Hydroelectric Dam, about 400 km north of Winnipeg, on the Saskatchewan River. This 66-m-high dam has dewatered about 8 km of the river upstream of Lake Winnipeg. In years of high spring flows, when spilling is necessary, fish can move upstream as far as the spillway. Closing of the spillway has resulted in the stranding of fish when the waters receded.

ONTARIO

No fish-mortality problems in relation to spillways have been identified in Ontario. This is not to say that mortality at hydroelectric installations is not important, only that priority has been given in recent years to fishery investigations at steam electric plants.

QUEBEC

Although no specific study has been carried out on fish mortality at spillways, a few problems have been identified.

At Lac Mégantic Dam, in the Eastern Townships, the energy dissipator, composed of vertical piles downstream of the spillway, has caused fish mortality. Observations on lake trout (Salvelinus namaycush and rainbow trout (Salmo gairdneri) revealed injuries from impact against the structures. At Lac Stukeley Dam, in the same region, adult brown trout (Salmo trutta) are sometimes stranded in the tailwater below the spillway. When flow decreases, trout are confined to small pools where overheating may cause death.

In the Trois-Rivières region, operation of the spillway at St-Narcisse Dam on the Batiscan River has been reported to cause problems. Walleye (Stizostedion vitreum, white sucker (Catostomus commersoni), longnose sucker (Catostomus catostomus, silver redhorse (Moxostoma anisurum), shorthead redhorse (Moxostoma macrolepidotum) and american shad (Alosa sapidissima spawn downstream of the spillway. In 1979, closing of the spillway gates during the incubation period caused the dewatering of part of the river downstream of the dam and drying of fish eggs. Muskellunge (Esox masquinongy), spawning on flooded lands in spring, were also probably affected. In 1980, an agreement was concluded with Hydro-Quebec to keep the water level sufficiently high to allow for hatching. The same problem of eggs drying is believed to occur at La Gabelle Dam, on the St-Maurice River, in the same region. These problems are not related to the characteristics of the spillways, but to their schedules of operation.

Another problem identified was associated with spillway operation of Mitis Dam on the Mitis River, in the Bas St-Laurent-Gaspésie region. During the fall of 1968, observations revealed that the river flow became unfavourable for young salmon (Salmo salar), which became vulnerable to predation from birds such as crow and gull. Following these observations, attempts were made to negotiate for minimal flow downstream of the dam (Côté 1974).

On the Mitis River, Mitis II Dam represents a barrier to the Atlantic salmon spawning migration. To bypass this problem, adult salmon are trapped at the foot of the dam and released upstream. On their downstream migration, adult and young salmon must progress past the dam. Since the turbine inlets are screened for trash removal, adults migrate through spillways, but young salmon pass either through turbines or spillways. When being carried through turbines, the mortality of young salmon is expected to be between 10% and 25%. Although mortality of fish passing over the 24-m dam is not expected to be high, biologists are concerned and would like to further investigate this aspect of the fish-conservation problem.

In the Saguenay-Lac St-Jean region, no fish-mortality problems have been reported, but a few spillways have been pointed out as possibly problematical because of high heads. These are the Chute à Caron Dam, on the Saguenay River; the three dams on the Péribonca River; the Ile Maligne, Lac Pipmuacan, Lamotte Reservoir and Onatchiway dams on the Shipshaw River; and the dams on the Aux Sables River and Chicoutimi River. No anadromous fish are involved in downstream movements through spillways, but landlocked salmon (Salmo salar), walleye (Stizostedion vitreum and northern pike (Esox lucius) could be injured.

The largest dam in the province of Quebec is LG-2, on La Grande River in the James Bay area. Its spillway, whose capacity is 1,982 m^3/sec, has been planned to operate only once every seven years, for a period of one and a half to two months. However, because of current construction activities at the dam, the spillway has been in operation continuously since September, 1979. No fish mortality has been reported.

Another important hydroelectric development in Quebec is the Manic-Outardes complex. Because of its remoteness, it did not receive much attention from provincial biologists. Possible problems arising from spillway characteristics and operation have not been assessed.

MARITIME PROVINCES

High spillways at dams in the Maritime Provinces are the exception rather than the rule. Fishery workers do not consider passage over these dams to pose a threat to fish populations (mostly Atlantic salmon). Nor do they believe gas supersaturation due to spillway discharges is a problem on any Maritime river.

One current concern, however, involves downstream fish passage at the 32-m-high spillway on the Nepisiguit River in New Brunswick. Salmon were previously blocked from moving upstream of the hydroelectric site by a falls about 30 m high. In recent years, salmon have been transported upstream of the development and concern has been expressed for downstream migrants that might impact on the rock base of the spillway.

Fishery workers also expressed the opinion that passage through hydroelectric impoundments may pose a more serious threat to Atlantic salmon smolts in the Maritimes than passage over or through spillways.

NEWFOUNDLAND

Supersaturation of nitrogen in waters below spillways is not believed to be a problem and there has not been any reports of fish suffering from gas-bubble disease in Newfoundland. However, studies have not been undertaken to determine whether or not nitrogen supersaturation does occur below spillways.

The problem of the sporadic kills of whitefish below the Lobstick control structure at the Churchill Falls power development (see page 2) remains unresolved. Some form of deterrent to repel whitefish from entering the tailrace below the dam was investigated. Although certain chemicals and devices tested under experimental conditions did produce a limited avoidance response from whitefish, numerous extraneous factors which could not be controlled severely limited the usefulness of the experiment. At present, the fish kills are apparently being considered within the context of the production dynamics of the lake whitefish population.

CANADIAN OVERVIEW

Spillways are not currently perceived to be a serious cause of fish mortality in Canada. Baxter and Claude (1980), in their exhaustive review of the environmental effects of dams in Canada, did not identify spillways as even a potential cause of mortality to fish. Contacts with regional and provincial fishery-resource agencies during this review have confirmed that general impression.

This review has indicated that fish losses (mostly salmon) at spillways could be and has been important in specific instances where dams have been high enough to inflict mortality to downstream migrants, e.g., the Cleveland Dam on the Capilano River in British Columbia.

Operation of spillways has also been identified as causing specific problems, with fish becoming stranded or attracted below them, and then killed by extreme hydraulic turbulence when spillway gates were opened. These instances, however, are infrequent and the magnitude of total fish losses in Canada due to spillways must be considered to be relatively insignificant in terms of total freshwater-fish production. This is not to say that isolated instances of fish losses associated with spillways is not important on a local scale. Hopefully, the information collected during the present review will form a basis for addressing existing fishery-conservation problems at spillways and for eliminating or mitigating future problems associated with their design or operation.

One important indirect effect of some spillways in Canada is their potential for causing atmospheric gas supersaturation in waters below dams, resulting in gas-bubble disease in fish. This problem is known to exist in three rivers in British Columbia. Although supersaturation resulting from spillways was not identified at other locations in Canada, it remains as the most serious potential fish-conservation problem associated with spillways.

GUIDELINES FOR SPILLWAY DESIGN AND OPERATION TO REDUCE FISH MORTALITY

Because this review has revealed few fishery-related problems at spillways in Canada, it is difficult to be specific in the formulation of design and operating guidelines to prevent injury to fish. An attempt was made to review possible federal-government guidelines on this subject. A recent change to the Canada Fisheries Act initiated the formation of a federal government task force that was to produce guidelines relevant to protecting fish at hydroelectric spillways. Contact with appropriate federal fisheries personnel, however, disclosed that no progress has been made.

Despite the apparent low level of concern for fish injury at spillways in Canada, a review of relevant literature and contact with U.S. and Canadian fishery workers has identified a number of potential causes of injury to fish. These injuries can either be a direct result of a spillway causing physical damage or be an indirect result of a spillway changing the fishes' environment. Examples of direct physical injury are:

1. Abrasion against concrete spillway.
2. Impact against base of spillway.
3. Turbulence and shearing forces in tailwater.
4. Impact of fish in free fall entering stilling basin.

Examples of indirect injury are:

1. Gas-bubble disease below spillways.
2. Predation above and below spillways.
3. Elevated water temperatures below spillways.
4. Dewatering and stranding of fish below spillways.

Obviously, these different kinds of potential problems do not occur at all spillways. In fact, at most spillways up to about 30 metres in height, critical fish-conservation problems associated with downstream passage are uncommon. The potential for injury or serious losses at relatively high dams, however, makes it important to consider design or operating procedures that would mitigate the impact. The present review provides a basis for making general suggestions for spillway design and operation that may eliminate or reduce their detrimental effects.

PROPOSED GUIDELINES

The degree of severity of injury is influenced not only by the height and design of the structure, but also by the species and age of fish passing through it. Thus, guidelines must be general in nature, and any specific design and operating requirements will require site-specific investigations. General guidelines are provided for each of the eight categories of fish injury identified. An occasional guideline may be contradictory to others.

In such instances a value judgement must be made in terms of choosing the most logical compromise.

1. Abrasion against concrete spillway

   - Minimize length of concrete chutes.
   - Use ski-jump spillways wherever possible to reduce or eliminate chutes.
   - Provide streamlined channels - provide a smooth concrete (contact) surface.
   - Minimize chute velocities, particularly in unlined (rock-cut) spillway channels.

2. Impact against base of spillway

   - Direct flow away from base of dam or spillway.
   - Ensure wind effects are minimized.
   - Provide discharge basin with sufficient depth to minimize impact of jet on basin floor.

3. Turbulence and shearing forces in tailwater

   - Minimize concentration of flow during operation if possible - operate spillway over 24 hours instead of 8-12 hr/day.
   - Reduce rate of dissipation of energy (increase the volume of water in the stilling basin) by increasing the length of crest of the spillway, deepening the pool at the base of the spillway, or increasing the cross-sectional area of the spill by aeration.

4. Impact of fish in free fall entering stilling basin

   - Not a problem when fish to be protected are less than about 13 cm long, since their terminal velocities will not reach the lethal velocity of 16 m/s.
   - Limit free fall of fish to 15 m-30 m in height, depending on size of fish to be protected.
   - Use ogee or other type of spillway to eliminate or limit free-fall portion.
   - Schedule flow releases for times when downstream fish migrations are minimal. (Some fish migrations may occur during a relatively discrete time within a 24-hr period.) This option is possible only if another route is available for downstream migrants.

5. Gas-bubble disease below spillways

   - Install, or include in design, spillway deflectors to direct flow horizontally into the stilling basin. These concrete sills are about 3.8 m in horizontal length and are placed near the base of spillways on dams located on the Columbia River system. They are designed with straight horizontal and vertical sides and attain best flow conditios for discharge up to the 1-in-10 year flood.
   - Do not include a plunge pool.

6. Predation above and below spillways

   - Vary spill procedures experimentally to eliminate or reduce concentrations of fish above spillways.
   - Design and operate spillways for minimum backroll in the stilling basin.
   - Design spillway outlet for smooth flow transition to the stream environment.

7. Elevated water temperatures below spillways

   - If the reservoir thermally stratifies, use submerged intakes for water withdrawal from lower reservoir depths. This strategy may have to be tempered by potential adverse effects caused by low oxygen levels and high ammonia levels in eutrophic reservoirs.

8. Dewatering and stranding of fish below spillways

   - Provide minimum downstream discharge.
   - Avoid sudden closures of gates.
   - Excavate discharge channel to downstream river to eliminate creation of ponds upon dewatering.

Before modification to the design or operation of spillways to protect fish is considered, it is important to identify the kinds of fish-conservation problems that need mitigation. Only after the specific problem or problems have been identified and described in terms relevant to the protection of fish, can the spillway designer or operator incorporate appropriate mitigating measures. In most cases in Canada, early consideration of fish mortality at spillways will result in appropriate design and operation. The exception to this general statement would be spillways at high dams located on rivers supporting runs of anadromous fish. Even in these instances, early identification of fish-conservation problems will ensure appropriate consideration is given during the feasibility and design stage of the project.

OTHER REMEDIAL MEASURES

Besides modifying the design and operation of spillways, other methods can be utilized to protect fish populations endangered by spillways and flow-control structures. Where no satisfactory design or operating procedures exist to protect fish (almost exclusively anadromous salmonids) from injury during their descent over high spillways, three methods for reducing the impact on fish stocks have been developed:

1. Artificial propagation of fish to replace lost stocks.

2. Interception and collection of fish at a site upstream of the dam for transport to safe areas below.

3. Utilization of screening devices to prevent fish entrainment, with provisions to convey them downstream by a bypass channel or other means.

These methods have been discussed earlier and elaboration of their respective merits and shortcomings will not be repeated here. At all dams less than about 35 metres in height, egress from the reservoir by way of the spillway will probably represent the safest route. According to the 1970 Registry of Dams in Canada, 85% are less than 35 m in height (Table 4). The registry includes all dams over 16 m in height. Dams between 10 m and 15 m are included if they comply with at least one of the following conditions:

1. The length of crest of the dam to be not less than 488 m.

2. The capacity of the reservoir formed by the dam to be not less than 99,000 m^3.

3. The maximum flood discharge dealt with by the dam to be not less than 2,000 m^3/sec.

4. The dam had specially difficult foundation problems.

5. The dam was of unusual design.

Dams up to 10 m in height are not included in the register.

TABLE 4. The number of Canadian dams in different height categories.

Dam-height category (m)	No. of dams	% of total	Accum. no.	Accum. %
Up to 15	149	34	190	34
16-20	110	25	259	59
21-25	47	11	306	70
26-30	43	10	349	80
31-35	22	5	371	85
36-40	15	3	386	88
41-45	11	3	397	91
46-50	3	1	400	92
51-55	7	2	407	94
56-60	7	2	414	95
60	21	5	435	100

The two principal routes for downstream-migrating fish to bypass hydroelectric dams are through the turbines and over the spillway. Much of the current downstream-fish-passage effort on the Columbia River system is devoted to encourage salmonid migrants to take the spillway route and hence avoid turbine-induced mortalities of from 10% to 20%. This option is preferred over artificial propagation, interception and transfer, or screening of turbine intakes.

Care should be taken to avoid costly fish-passage measures, which in themselves may impose fish mortality equal to or greater than caused by passage through spillways. In almost every case, the assessment of spillway mortality must be made in conjunction with turbine-related mortality and other environmental effects that might impose stress on fish populations. Usually, after such an assessment at dams less than about 35 metres in height, egress by way of the spillway will be identified as the safest route.

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